Lecture Overview

• focus cues & the vergence-accommodation conflict

• advanced optics for VR with focus cues:
  • gaze-contingent varifocal displays
  • volumetric and multi-plane displays
  • near-eye light field displays
  • Maxwellian-type displays

• AR displays
Magnified Display

- big challenge: virtual image appears at fixed focal plane!
- no focus cues

\[
\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}
\]
Importance of Focus Cues Decreases with Age - Presbyopia

Age (years)

0D (∞cm)
4D (25cm)
8D (12.5cm)
12D (8cm)
16D (6cm)
Relative Importance of Depth Cues

Cutting & Vishton, 1995
The Vergence-Accommodation Conflict (VAC)
Stereopsis (Binocular)

Oculomotor Cue

Vergence

extraocular muscles

Focus Cues (Monocular)

Accommodation

ciliary muscles

relaxed

contracted

Visual Cue

Binocular Disparity

Retinal Blur
Stereopsis (Binocular)

Oculomotor Cue

Vergence

Blur Cues (Monocular)

Accommodation

Visual Cue

Binocular Disparity

Retinal Blur
Stereopsis (Binocular)

Oculomotor Cue

Vergence

Visual Cue

Binocular Disparity

Focus Cues (Monocular)

Accommodation

Extraocular muscles

Relaxed

Contracted

Ciliary muscles

Retinal Blur
Real World: Vergence & Accommodation Match!
Current VR Displays:
Vergence &
Accommodation
Mismatch
Accommodation and Retinal Blur

Conventional Display

0.25m (4D)  0.3m (3.33D)  0.35m (2.86D)  0.5m (2D)  0.7m (1.43D)  1 m  2m (0.5D)  ∞ (0D)
Blur Gradient Driven Accommodation

Conventional Display

0.25m (4D)  0.3m (3.33D)  0.35m (2.86D)  0.5m (2D)  0.7m (1.43D)  1 m  2m (0.5D)  ∞ (0D)
Blur Gradient Driven Accommodation

Conventional Display

Virtual image of screen

0.25m (4D)  0.3m (3.33D)  0.35m (2.66D)  0.5m (2D)  0.7m (1.43D)  1 m  2m (0.5D)  ∞ (0D)
Blur Gradient Driven Accommodation

Conventional Display

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0.25m (4D)  0.3m (3.33D)  0.35m (2.66D)  0.5m (2D)  0.7m (1.43D)  1 m  2m (0.5D)  ∞ (0D)
Blur Gradient Driven Accommodation

Conventional Display

virtual image of screen

0.25m (4D)  0.3m (3.33D)  0.35m (2.86D)  0.5m (2D)  0.7m (1.43D)  1 m  2m (0.5D)  \( \infty \) (0D)
Blur Gradient Driven Accommodation

Conventional Display

![Image of animals looking at a screen with their eyes]
Blur Gradient Driven Accommodation

Conventional Display
Real World:

Vergence & Accommodation Match!
Stereo Displays Today (including HMDs):

Vergence-Accommodation **Mismatch!**
VR Displays with Focus Cues

1. Gaze-contingent Varifocal Displays
Fixed Focus Displays

\[
\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}
\]
Varifocal Displays

actuator $\rightarrow$ vary $d'$

Lens

Display

$\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}$
Varifocal Displays

Magnified Display

\[ \frac{1}{d} + \frac{1}{d'} = \frac{1}{f} \]
Varifocal Displays - History

- M. Heilig “Sensorama”, 1962 (US Patent #3,050,870)
- S. Shiwa, K. Omura, F. Kishino “Proposal for a 3-D display with accommodative compensation: 3DDAC”, JSID 1996
- S. McQuaide, E. Seibel, J. Kelly, B. Schowengerdt, T. Furness “A retinal scanning display system that produces multiple focal planes with a deformable membrane mirror”, Displays 2003
- S. Liu, D. Cheng, H. Hua “An optical see-through head mounted display with addressable focal planes”, Proc. ISMAR 2008

Manual focus adjustment
Heilig 1962

Automatic focus adjustment
Mills 1984

Deformable mirrors & lenses
McQuaide 2003, Liu 2008
Conventional Stereo / VR Display

- Conventional
- Stereoscopic distance
- Virtual image distance
- Stereoscopic distance
- Vergence
- Accommodation
Removing VAC with Varifocal Displays

With Focus Cues

stereoscopic distance

virtual image distance

stereoscopic distance

vergence
accommodation
Follow the target with your eyes.
Accommodative Response

Conventional

Dynamic Focus

stereoscopic distance

virtual image distance

Padmanaban et al., PNAS 2017

Accommodative Response

Relative Distance [D]

Time [s]
Accommodative Response

n = 59, mean gain = 0.29

Padmanaban et al., PNAS 2017
Accommodative Response

Padmanaban et al., PNAS 2017
Accommodative Response

Relative Distance [D] vs Time [s]

- Stimulus
- Accommodation

n = 24, mean gain = 0.77

Padmanaban et al., PNAS 2017
Do Presbyopes Benefit from Dynamic Focus?

Padmanaban et al., PNAS 2017
Do Presbyopes Benefit from Dynamic Focus?

Padmanaban et al., PNAS 2017
Do Presbyopes Benefit from Dynamic Focus?

Padmanaban et al., PNAS 2017

![Graph showing age vs gain with conventional and dynamic focus lines](image)
Do Presbyopes Benefit from Dynamic Focus?

Gain

- conventional
- dynamic

Age

Response for Physical Stimulus
Heron & Charman 2004
Gaze-contingent Varifocal Displays

- non-presbyopes: adaptive focus is like real world, but needs eye tracking!
Gaze-contingent Varifocal Displays

Padmanaban et al., PNAS 2017
Gaze-contingent Varifocal Displays

Padmanaban et al., PNAS 2017
Summary

- adaptive focus drives accommodation and can also correct for refractive errors (myopia, hyperopia)

- gaze-contingent focus gives natural focus cues for non-presbyopes, but require eyes tracking

- presbyopes require fixed focal plane with correction
VR Displays with Focus Cues

2. Multiplane Displays
Multiplane VR Displays

- Schowengerdt B, Seibel E (2006) True 3-d scanned voxel displays using single or multiple light sources. JSID
- Love GD et al. (2009) High-speed switchable lens enables the development of a volumetric stereoscopic display. Optics Express
- … many more …

idea introduced
Rolland et al. 2000

benchtop prototype
Akeley 2004

near-eye display prototype
Liu 2008, Love 2009
Multiplane VR Displays

- Schowengerdt B, Seibel E (2006) True 3-d scanned voxel displays using single or multiple light sources. JSID
- Love GD et al. (2009) High-speed switchable lens enables the development of a volumetric stereoscopic display. Optics Express
- … many more …

biggest problem: flicker
VR Displays with Focus Cues

3. Light Field Displays
Light Field Cameras

Light Field Stereoscope

Huang et al., SIGGRAPH 2015
Near-eye Light Field Displays

Idea: project multiple different perspectives into different parts of the pupil!
Target Light Field

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey
Multiplicative Two-layer Modulation

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey
Multiplicative Two-layer Modulation

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey
Multiplicative Two-layer Modulation

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey
Multiplicative Two-layer Modulation

\[ \text{minimize} \| \beta I - (\phi_1 t_1) o (\phi_2 t_2) \|^2 \]
\[ \{ t_1, t_2 \}, \quad \text{s.t.} \quad 0 \leq t_1, t_2 \leq 1 \]

Reconstruction:
\[ t_1 \leftarrow t_1 o \frac{\phi_1^T (\beta I o (\phi_2 t_2))}{\phi_1^T (I o (\phi_2 t_2)) + \epsilon} \]
for layer \( t_1 \)

Tensor Displays, Wetzstein et al. 2012

Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey
Light Field Stereoscope

Traditional HMDs - No Focus Cues

The Light Field HMD Stereoscope

Huang et al., SIGGRAPH 2015
Light Field Stereoscope

Traditional HMDs - No Focus Cues

The Light Field HMD Stereoscope

Huang et al., SIGGRAPH 2015
Traditional HMDs - No Focus Cues

The Light Field HMD Stereoscope

Huang et al., SIGGRAPH 2015

Model Courtesy of Paul H. Manning
Light Field Stereoscope

Traditional HMDs - No Focus Cues

The Light Field HMD Stereoscope

Huang et al., SIGGRAPH 2015

Model Courtesy of Paul H. Manning
Tensor Displays

Wetzstein et al., SIGGRAPH 2012
Vision-correcting Display

printed transparency

iPod Touch prototype

Huang et al., SIGGRAPH 2014
300 dpi or higher

Huang et al., SIGGRAPH 2014
VR Displays with Focus Cues

4. Maxwellian-type Displays
Blur Gradient Driven Accommodation

Conventional Display

Accommodation-dependent Point Spread Functions

virtual image of screen

0.25m (4D) 0.3m (3.33D) 0.35m (2.86D) 0.5m (2D) 0.7m (1.43D) 1m 2m (0.5D) ∞ (0D)
PSF Engineering

Conventional Display  Accommodation-invariant Display

Accommodation-dependent Point Spread Functions

Accommodation point spread functions are shown for different distances: 0.25m (4D), 0.3m (3.33D), 0.35m (2.86D), 0.5m (2D), 0.7m (1.43D), 1m, 2m (0.5D), and ∞ (0D).

The virtual image of the screen is depicted at the right side of the diagram.
Q: can we drive accommodation with stereoscopic cues by optically removing the retinal blur cue?
How do we remove the blur cue?
Aperture Controls Depth of Field

Image courtesy of Concept One Studios
Aperture Controls Depth of Field

Image courtesy of Concept One Studios
Aperture Controls Depth of Field

Image courtesy of Concept One Studios
Maxwellian-type (pinhole) Near-eye Displays

Point Light Source
Maxwellian-type (pinhole) Near-eye Displays

Severely reduces eyebox; requires dynamic steering of exit pupil
Focal Sweep

EDOF Cameras:
Nagahara et al., ECCV 2008
Cossairt et al., SIGGRAPH 2010
Convolution
Convolution

*  

=  

Diagram illustrating the concept of convolution in signal processing.
Target

Conventional

AI @ 3D

Conventional Display @ 3D
Stimulus

Distance (D)

Accommodation Invariant

Dynamic

Gain: 0.61

Gain: 0.85
Measured User Response

Conventional

Gain: 0.35
Measured User Response

Distance (D)

Accommodation Invariant

Time (s)

Gain: 0.61

Dynamic

Time (s)

Gain: 0.85

Conventional

Time (s)

Gain: 0.35

Stimulus

Average
Now: benchtop

Future: multifocal lenses
Overview of Optical See-through AR Displays
Thin Beam Combiner?
Thin Beam Combiner!
Pepper’s Ghost 1862
OST AR - Case Studies
Meta 2

• larger field of view (90 deg) than Glass

• also larger device form factor
Microsoft HoloLens
Microsoft HoloLens

- diffraction grating
- small FOV (30x17), but very good image quality
Microsoft HoloLens 2

- laser-scanned waveguide display
- claimed 2K resolution per eye (2560x1440), probably via “interlaced” scanning
- field of view: 52° diagonally (3:2 aspect, 47 pixels per visual degree)

Video-based AR: ARCore, ARKit, ARToolKit, …
Challenges: Eye Box vs Field of View
Challenges: Eye Box vs Field of View

- Need small entrance pupil (small device) and large exit pupil (large eye box) - pupil needs to be magnified
Challenges: Eye Box vs Field of View

- need small display (small device) but large field of view – image needs to be magnified
Challenges: Eye Box vs Field of View

- pupil needs to be magnified
- image needs to be magnified

Can’t get both at the same time – etendue!
Challenges: Eye Box vs Field of View

- possible solutions: exit pupil replication (loss of light), live with small FOV (not great), dynamically steer eye box (mechanically difficult), ..
Challenges: Chromatic Aberrations

- thin grating couplers create chromatic aberrations
Challenges: Chromatic Aberrations

volume holographic couplers, e.g. TruLife Optics

stacked waveguides

• all solutions have their own problems: ease of manufacturing, yield, robustness, cost, …
Case 1: digital in front of physical

Case 2: physical in front of digital

→ difficult: need to block real light!

→ easy: don’t render digital object everywhere
Next Lecture: Inertial Measurement Units I

- accelerometers, gyros, magnetometers
- sensor fusion
- head orientation tracking